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# Air quality impacts of a scheduled 36-h closure of a major highway

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## HIGHLIGHTS

- ► Air pollutants were examined around the time of a major planned freeway closure.
- ► On the closure day, particle number concentration (PNC) downwind of the freeway was reduced by 83%.
- ► On the closure day, $PM_{2.5}$ decreased by 18–36% across the South Coast Air Basin.
- ► Weekday downwind PNC decreased by 60% between 2001 and 2011.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Elevated concentrations of ultrafine particles (UFPs, <0.1 μm) are commonly found near roadways. On the July 16–17, 2011 weekend, a section of a major Los Angeles freeway, the I-405, was closed for 36 h. We measured UFPs and other pollutants at two fixed locations, one upwind and one downwind, and at various distances from I-405 using a mobile measurement platform (MMP) on Fridays, Saturdays, and Sundays before, during, and after closure. On the closure Saturday on July 16, I-405 traffic flow was reduced by ~90% relative to non-closure Saturday observations. Downwind of I-405, fixed-site measurements showed the following reductions: 83% of particle number concentration (PNC), 36% of $PM_{2.5}$, and 62% of black carbon. Fixed-site measurements showed daily average UFP size distributions were bimodal for non-closure conditions (nucleation modes ~20 nm, accumulation modes ~60 nm), but only showed an accumulation mode ~50 nm during closure. Spatial measurements from the MMP confirmed no nucleation mode was detected at any location 0–300 m downwind during closure. In 2011, non-closure particle emission factors were 5.0, 2.7, and 3.4 × $10^{13}$ particles vehicle$^{-1}$ km$^{-1}$ for Friday through Sunday respectively. After accounting for instrumental and traffic flow differences, weekday PNC in 2011 was 60% lower than 2001 at the same study location. During the closure event, regional freeway traffic was reduced compared to four selected control Saturdays. Eight stationary monitoring stations throughout the South Coast Air Basin showed $PM_{2.5}$ was reduced between 18 and 36% relative to the same control days. The outcome of this natural experiment during the I-405 closure confirms that substantial traffic reduction can improve local and regional air quality in sprawled urban regions such as Los Angeles, CA.



## 1. Introduction

Exposure to traffic-related air pollutants has been linked to adverse health effects by epidemiological cohort studies (e.g.

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Beelen et al., 2007; Laden et al., 2006). Several other epidemiological studies have specifically supported the adverse health effects of exposure to ultrafine particles (UFPs, <0.1 μm) in addition to fine and/or coarse particulate matter (PM) (Ibald-Mulli et al., 2002; Klot et al., 2002). de Kok et al. (2006) reported in a comprehensive review of toxicology studies that the mutagenicity potential and cellular toxicity of PM is highest within smaller size fractions. Donaldson et al. (2001) suggested an explanation for elevated toxicity when particle size distributions are skewed toward smaller size fractions is because total particulate surface area increases.

Many studies have characterized PM from traffic emissions. Particle number concentrations (PNC) measured on roadways can range $\sim 10^5$–$10^6$ particles $cm^{-3}$, depending upon meteorology and traffic configurations such as driving speed, traffic flow (vehicles $hour^{-1}$), and fleet composition (e.g. Kittelson et al., 2004; Zhu et al., 2008). PNC downwind from a roadway decreases exponentially with increasing distance and particle size distribution shifts rapidly as concentration decreases (Hitchins et al., 2000; Pirjola et al., 2006; Zhu et al., 2002b).

Due to the significant contribution of air pollutants from traffic emissions, traffic calming policies such as traffic restriction could be a rational strategy to mitigate urban air pollutants. During the 1996 Olympic Games in Atlanta, peak traffic flow and ozone reduced ~20 and ~30% respectively (Friedman et al., 2001), but further analysis by Peel et al. (2010) indicates meteorology may have played a role since similar ozone reductions were found across the region. In July 2004 during a four-day Democratic National Convention in Boston, Massachusetts, Levy et al. (2006) reported 42% $NO_2$ reductions in regions of decreased vehicle flow, but found no overall $PM_{2.5}$ decreases. During the 2008 Olympic and Paralympic Games in Beijing, the Chinese government enacted air pollution-reducing policies for both stationary and mobile sources; near-roadway black carbon (BC) concentrations decreased 73%, sulfur dioxide 61%, carbon monoxide 25%, and nitrogen oxides 21% (Wang et al., 2009a, 2009b). However, these studies were unable to identify the air quality improvements due to traffic restrictions alone since parallel stationary source reductions were mandated. In August 2008, Park Avenue in New York City was closed to vehicular traffic on three consecutive Saturday mornings to promote clean air which resulted in 58% lower UFP concentrations near-roadway (Whitlow et al., 2011). This study, however, was limited to the closure region and did not consider changes to the New York City as a whole. In summary, these previous traffic restriction events were associated with improved air quality, but have the noteworthy aforementioned limitations.

In July 2011, one of the busiest freeways in United States (~380,000 vehicles $day^{-1}$), the I-405, was scheduled for a two-day closure as part of a freeway improvement project. Months in advance, Caltrans[1] alerted the public to potential traffic jams. The closure event provided a valuable opportunity to conduct a natural traffic behavior and air quality experiment. The first objective of this study was to determine the impacts of this major freeway closure event, the so-called *Carmageddon*, on local traffic behavior and air quality. Second, we sought to compare the non-closure-weekday UFP concentrations measured during this study with measurements collected in 2001 at the same location (Zhu et al., 2002b). Since most emission control programs occur over long periods of time, and impacts are even more gradual, comparison over this ten-year period enables a strong evaluation of their efficacy. A third objective was to explore the changes of regional traffic and air quality as a result of the localized closure.

[1] Caltrans: California Department of Transportation.

## 2. Methods

### 2.1. Study design

The I-405 closure event began midnight of Friday July 15 and remained in effect for 36 h until 12:00 on Sunday July 17. Fixed-site measurements were conducted between 10:00 and 20:00 for three consecutive Friday through Sunday periods: sampling days included Friday through Sunday July 8–10 (pre-closure period), Friday July 15, Saturday and Sunday July 16 and 17 (closure period), and Friday through Sunday July 22–24 (post-closure period). Hereafter, we refer to the pre- and post-closure periods collectively as “non-closure”. The sampling time from 10:00 to 20:00 corresponded to consistent sea breeze conditions and the time of peak weekend traffic flow. Although the closure was scheduled for a weekend, we included Friday measurements between 10:00 and 20:00 to correspond to the protocol used by Zhu et al. (2002b) for non-closure weekday comparison. Moreover, traffic changes were expected on Friday July 15 due to on- and off-ramp closures which began around 20:00. Thus, the closure may have affected measurements on Friday July 15, the day immediately before the closure. Accordingly, Friday July 15 measurements are not classified as either non-closure or closure. Full-closure conditions were measured from 10:00 to 20:00 on Saturday July 16, and from 10:00 to 12:00 on Sunday July 17.

### 2.2. Study location

Fig. 1 shows a map of the study location. All fixed-site and MMP[2] measurements took place on Constitution Avenue, a perpendicular cross street passing beneath I-405, approximately 5 km north of I-10 and 11 km south of US-101. The I-405 is elevated ~4.5 m above the surrounding terrain, generally north and south (actual orientation 330°), has a 1% upgrade heading north, and is situated in West Los Angeles ~6 km inland from the Santa Monica Bay and the Pacific Ocean. Sepulveda Boulevard is located immediately adjacent and to the east of I-405.

During closure, northbound lanes were completely closed for 16 km between I-10 and U.S. 101, southbound lanes for 8 km from U.S. 101 to Getty Center Drive. Traffic was permitted to enter I-405 southbound at Getty Center Drive and Sunset Boulevard, but travel was restricted to a single lane. Sepulveda remained open through the duration of the campaign. Constitution was closed to local access for July 16 and 17 only.

### 2.3. Instruments and measurements

Fixed-site measurements were conducted upwind and downwind of the freeway for all campaign days. The upwind fixed site was located along Constitution 50 m west of the freeway median. The downwind fixed site was 50 m east of the freeway median, east of Sepulveda north of Constitution (Fig. 1). Measurements at these fixed sites included particle size distribution, PNC, BC, $PM_{2.5}$, and $CO_2$ (Table 1). In order to make meaningful comparisons between data measured by the upwind and downwind sets of instruments, we corrected upwind data to downwind data using the linear equations to ranges (see Supplementary material, Section 1). All fixed-site DustTrak $PM_{2.5}$ data were divided by 2.4 to achieve corresponding gravimetric values. This correction factor was determined and used by Zhang and Zhu (2010) to analyze near-roadway $PM_{2.5}$, and is comparable to data reported by Yanosky et al. (2002).

[2] MMP: mobile measurement platform.

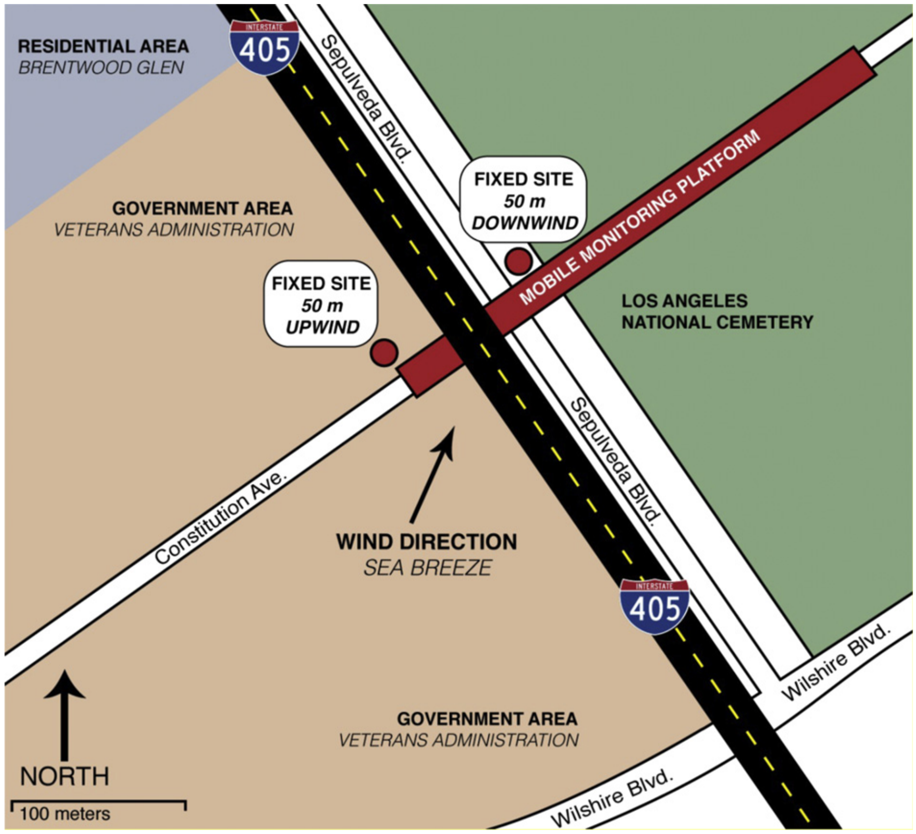


**Fig. 1.** Map of the study area, indicating the locations of the fixed-site measurements (50 m upwind, 50 m downwind), and route of the mobile monitoring platform (50 m upwind to 300 m downwind).

In addition to fixed-site measurements, an MMP was driven along Constitution (Fig. 1) to measure the spatial profile of vehicular emitted pollutants from I-405 and Sepulveda. Instruments and equipment installed on the MMP are also included in Table 1. MMP measurements were taken on campaign Saturdays only (July 9, 16, and 23). Each day between 11:00 and 16:00, measurements were made twelve times along Constitution, from 50 m upwind to 300 m downwind, and then in the reverse direction.

Since we focus on the extent of the freeway plume, occasional emissions from high-emitting vehicles on Constitution encountered during sampling were removed by reviewing video and audio records. Close proximity of the MMP to a high emitter can result in concentrations >100,000 particles $cm^{-3}$ (exceeding the background concentration by a factor of >20) in an isolated plume usually limited to a few tens of meters (Hu et al., 2012). Removing high emitters does not change the overall trend, but makes the freeway plumes less noisy. Details about the instrument power supply, sampling manifold, calibration, and instrument synchronization and flow checks are available elsewhere (Choi et al., 2012; Hu et al., 2009; Kozawa et al., 2009; Westerdahl et al., 2005). All instruments were synchronized on a daily basis. Inter-comparison among instruments used at fixed-site and MMP are given in the Supplementary material, Section 2.

### 2.4. Traffic and meteorology

Traffic flow on Sepulveda was video recorded for every five out of 15 min. Subsequent manual counting classified vehicles by type: cars and diesel trucks. We observed a traffic speed of ~56 km $h^{-1}$ along Sepulveda during free flow traffic conditions, and ~10 km $h^{-1}$ during congested periods. These values were used in calculation of traffic density for Sepulveda. Total traffic and HDDT[3] flows on I-405 were measured by the PeMS,[4] which provides historical and real-time traffic flow and speed via Caltrans loop detectors from traffic management centers statewide (Choe et al., 2002). We used data from PeMS sensors on I-405 S 717795, and I-405 N 717798 and 717800. We divided traffic flow by speed to yield traffic density (vehicles $km^{-1}$), which represents the number of vehicles on a given segment of the roadway. Counts from these sensors are interpreted by Caltrans with an algorithm that omits unusual data, and replaces actual data with expected values. The extent of estimation is indicated by a “percent observed” parameter; we included only values >50% in our analyses. We verified PeMS data accuracy following the campaign. The accuracy of the PeMS traffic database is a salient issue because it has been used widely for air quality studies, for quantifying greenhouse gas emissions, and for managing traffic congestion (Barth and Boriboonsomsin, 2008; Skabardonis et al., 2003). We found, at our study location, up to 30% hourly error in heavy-duty diesel traffic (HDDT) flow. The methodology and results of this analysis are included in Supplementary material, Sections 4 and 5.

Meteorological data were obtained from a weather station located 1.6 km northeast of the study site, operated by the University of California Los Angeles (UCLA), Department of Atmospheric and Oceanic Sciences.

[3] HDDT: heavy duty diesel truck.
[4] PeMS: Performance Management System.

**Table 1**
Monitoring instruments used for the fixed sites upwind and downwind, and mobile platform (MMP) locations.

| Instrument | Measurement parameter | Resolution | Detection limit | Location(s) |
|---|---|---|---|---|
| TSI Portable CPC[a], Model 3007 | UFP count (10 nm–1 μm) | 1 s | 1–$10^5$ particles $cm^{-3}$ | MMP, Upwind |
| TSI FMPS[b], Model 3091 | UFP size (5.6–560 nm) | 1 s | 5.6 nm: 1–$10^7$ particles $cm^{-3}$; 560 nm: 1–$10^5$ particles $cm^{-3}$ | MMP |
| TSI SMPS[c] 3936L85, WCPC 3786 | UFP size (7.64–289 nm) | 120 s | 1–$10^7$ particles $cm^{-3}$ | Upwind |
| TSI SMPS 3936L85, WCPC 3785 | UFP size (7.64–289 nm) | 120 s | 1–$10^7$ particles $cm^{-3}$ | Downwind |
| TSI APS[d] Model 3321 | UFP size (0.5–20 μm) | 60 s | 1–$10^4$ particles $cm^{-3}$ | Downwind |
| TSI DustTrak, Model 8520 | $PM_{2.5}$ mass | 1 s | 0.001–100 mg $m^{-3}$ | Upwind, Downwind |
| EcoChem PAS 2000 | Particle bound PAH | 5 s | 0–2000 ng $m^{-3}$ | MMP |
| Magee Aethalometer Model AE-42-2 | BC | 60 s | 0.06–20 μg $m^{-3}$ | Downwind |
| TSI Q-Trak Model 8550 | $CO_2$ | 60 s | 0–5000 ppm | Upwind, Downwind |
| Teledyne-API Model 200E | $NO_x$, NO, $NO_2$ | 20 s | 0–20 ppm | MMP |
| Stalker LIDAR & Vision Digital System | Traffic characterization | 1 s | N/A | MMP |

[a] Condensation Particle Counter.
[b] Fast Mobility Particle Sizer.
[c] Scanning Mobility Particle Sizer.
[d] Aerodynamic Particle Sizer.

### 2.5. Comparison of weekday I-405 emissions between 2001 and 2011

We first compared PNC as measured by the SMPS by calculating emission factors (EFs)[5] as the number of particles emitted per kg fuel burned. This method using the change in $CO_2$ concentration as a proxy for fuel burned has been used in many near-source studies (Herndon et al., 2008; Kurniawan and Schmidt-Ott, 2006; Ntziachristos et al., 2007). Equation (1), adapted from Herndon et al. (2008), assumes a $CO_2$ emission index $EI(CO_2) = 3160$ g $CO_2$ $kg^{-1}$.

$$\mathrm{EF[particles/kg\text{-}fuel]} = (\Delta \mathrm{UFP})/(\Delta \mathrm{CO_2}) \times \mathrm{EI(CO_2)} \times (M_{\mathrm{air}}/M_{\mathrm{CO_2}}) \times (1/\rho_{\mathrm{air}}) \times \left(10^6 \mathrm{ppm}\right) \quad (1)$$

To obtain distance-based emission factors per vehicle, we assumed average fuel consumption rate and fuel density were 0.12 L $km^{-1}$ and 0.74 kg $L^{-1}$, respectively. We selected three days, Friday July 15, Saturday July 23, and Sunday July 24, with uninterrupted traffic flow, to achieve constant detectable $CO_2$ and PNC concentration signals between upwind and downwind sites (see Fig. 2). We excluded data where $\Delta CO_2 < 5$ ppm from our analysis. These results are reported in Section 3.2.1.

We then compared the ratio of downwind to upwind PNC for both 2001 and 2011. In contrast to EF calculations, this analysis was not limited to days with high differences between downwind and upwind $CO_2$ (Friday July 8 was the only non-closure weekday to which this applies). Thus by including all non-closure weekdays, an additional 10 h of observations on Friday July 22 were included. Furthermore, comparing the PNC ratio avoided instrumentation bias since counting sensitivities are different between the butanol-based condensation particle counter (butanol-CPC; TSI 3022) used by Zhu et al. (2002b) and the water-based CPC (WCPC; TSI 3785) used in this study. We compare SMPS size bin data from 2001 using a butanol-CPC (6–220 nm) and 2011 using a WCPC (7.64–289 nm). The larger upper boundary of particle sizes in 2011 (from 220 to 289 nm) did not influence the results significantly since our size-segregated EF analysis indicated ~3% roadway emissions were from the >100 nm size bin (Section 3.2.1).

In both 2001 and 2011, a consistent sea-breeze (southwesterly wind) was observed during the measurement periods, thus we can assume that the upwind locations are not affected by any combustion sources and the relative upwind PNC and size distributions did not appreciably shift between 2001 and 2011. This led us to attribute changes in upwind PNC measurements to different instrumentation. The computed ratio of upwind average PNC in 2001–2011 measurements was 6.7. We multiplied all 2011 data measured for this study (upwind and downwind) by this ratio to make them comparable to 2001 data. The results from this analysis are reported in Section 3.2.2.

### 2.6. Regional traffic and $PM_{2.5}$ assessment

We selected Saturdays that most closely matched the meteorological conditions (temperature, wind speed, relative humidity, and incoming solar radiation) of the closure Saturday, July 16, 2011. The identified control Saturdays were June 18 and 25, July 30, and August 13, 2011. We compare 24-h average traffic and $PM_{2.5}$ data for each of the control and closure days. Traffic data were obtained from the PeMS database at 18 locations in both directions of travel, which were combined and reduced to one data point per location. We report ratios of traffic flow change on the closure day relative to control days since we expect total traffic flow error to be reasonably constant over time (Supplementary material, Section 5) and to be canceled in reporting a ratio. Ambient $PM_{2.5}$ data were obtained from eight nearby monitoring stations in the South Coast Air Basin, for a 24-h period on each Saturday. The traffic flow and $PM_{2.5}$ at the closure site from this study were also included in the analysis, but this point only pertains to the 10:00–20:00 period.

## 3. Results and discussion

### 3.1. Near-roadway impacts

#### 3.1.1. Meteorology

Table 2 summarizes meteorological and traffic conditions during sampling campaign. The pre-closure period average wind speed was 3.0 m $s^{-1}$ and temperature was 22 °C. The during-closure period average wind speed was 4.3 m $s^{-1}$ and temperature 21 °C. The post-closure period average wind speed was 5.2 m $s^{-1}$ and temperature 21 °C. Daily-average wind speed and temperature were comparable within each period (±1 m $s^{-1}$ wind speed and ±1 °C), but differed somewhat across periods (Table 2). During the campaign, the wind direction plus or minus the standard deviation did not exceed 330° or decrease below 150°. The consistent sea breeze conditions enabled consistent comparisons of fixed sites upwind and downwind air quality parameters.

[5] EFs: emission factors.

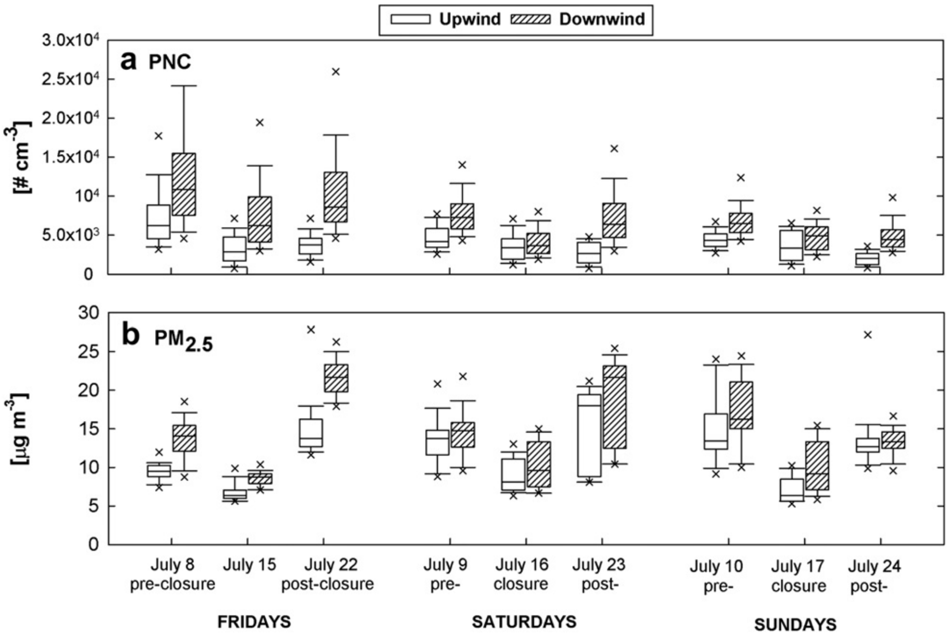


**Fig. 2.** Upwind and downwind box and whisker plots of (a) PNC and (b) $PM_{2.5}$. The boxes represent the interquartile range, the whiskers one and a half times the interquartile range, and the region bounded by the "X" symbols indicate the middle 95 percent of the data. One-minute resolution data were used for $PM_{2.5}$ and 2-min resolution data for PNC.

Hourly temperature, wind speed, and relative humidity were each grouped by pre-, during, and post-closure periods. Each period of hourly observations ($n = 30$) was tested for inter-period differences using a pooled-variance $t$-test. Meteorological data collected during closure were not significant different from post-closure period, but significantly different from the pre-closure period. Thus, the subsequent air pollution data analysis focuses on comparison between closure and post-closure periods.

### 3.1.2. *Traffic*

Table 2 also shows I-405 and Sepulveda hourly average traffic flow between 10:00 and 20:00. Non-closure I-405 and Sepulveda combined traffic flow was ~12% higher on weekends (Saturdays and Sundays) than on Fridays (~19.1 × $10^3$ and ~17.1 × $10^3$ vehicles $hour^{-1}$, respectively); traffic speed was ~36% higher on weekends than on Fridays (83 and 61 km $h^{-1}$, respectively); and this equates to a traffic density ~16% lower on weekends than Fridays (~238 and ~285 vehicles $km^{-1}$, respectively). Our observed traffic flow decreases on Fridays are characteristic of the classic "backward bending" of highway traffic speed-flow relationships originally elucidated by Walters (1961) when traffic demand approaches capacity (Walters, 1961). Time series traffic flow data measured at our sampling site are included in the Supplementary material.

The closure event corresponded to reduced I-405 traffic flow on Saturday July 16 by 90% (to 1.6 × $10^3$ vehicles $hour^{-1}$), and Sunday July 17 by 40% (to 6.3 × $10^3$ vehicles $hour^{-1}$), of the average non-closure weekend traffic flow. Sepulveda traffic flow was reduced on Saturday and Sunday by 20% from non-closure conditions. This behavioral response suggests freeway traffic was not diverted onto immediately adjacent local street alternatives, but instead an absolute traffic flow reduction from the transit corridor, the combination of I-405 and Sepulveda between I-10 and I-101, occurred in response to the intense warnings by public officials of potential chaotic congestion (i.e., "*Carmageddon*"). Consistent with this behavioral response, no large-scale traffic jams were observed in the area. Substantial net traffic spillover from the during-closure weekend to non-closure weekend was not observed either, since the seasonal I-405 weekend average flow (18,200 vehicles $hour^{-1}$) was comparable to the pre- and post-closure weekends. Weekend-to-weekday spillover was also insubstantial, since traffic flow on Friday July 15 and Monday July 18 were 9.5% and 6.8% lower than

**Table 2**
Summary of meteorological and traffic conditions during sampling campaign. Data displayed as: average value from 10:00–20:00 (standard deviation).

| Day in July 2011 | Pre-closure | | | Closure | | | Post-closure | | |
|---|---|---|---|---|---|---|---|---|---|
| | 8 | 9 | 10 | 15 | 16 | 17 | 22 | 23 | 24 |
| | Fri | Sat | Sun | Fri | Sat | Sun | Fri | Sat | Sun |
| *Meteorology* | | | | | | | | | |
| Temperature (°C) | 23 (2) | 22 (1) | 22 (1) | 21 (1) | 21 (1) | 22 (1) | 21 (1) | 21 (1) | 20 (1) |
| Wind speed (m $s^{-1}$) | 3.0 (0.7) | 3.0 (0.8) | 3.0 (1.0) | 5.2 (2.9) | 4.3 (2.4) | 5.0 (3.2) | 5.2 (3.2) | 4.9 (3.1) | 5.4 (3.4) |
| Wind direction (°) | 195 (25) | 199 (28) | 196 (36) | 216 (27) | 204 (45) | 191 (30) | 208 (35) | 210 (30) | 190 (24) |
| Relative humidity (%) | 74 (5) | 78 (4) | 77 (4) | 68 (4) | 74 (7) | 75 (2) | 79 (5) | 76 (5) | 80 (3) |
| *Traffic volume* | | | | | | | | | |
| I-405 Freeway ($10^2$ $h^{-1}$) | 160 (33) | 180 (23) | 188 (11) | 150 (35) | 16 (2) | 63 (20) | 151 (31) | 177 (16) | 184 (20) |
| Sepulveda Boulevard ($10^2$ $h^{-1}$) | 16 (5) | 11 (4) | 7 (2) | 10 (4) | 9 (2) | 6 (3) | 15 (5) | 11 (3) | 8 (3) |
| Average speed (km $h^{-1}$)[a] | 69 (22) | 80 (13) | 102 (6) | 80 (29) | 76 (1.6) | 90 (3) | 53 (22) | 64 (21) | 86 (18) |
| Density (vehicles $km^{-1}$)[a] | 255 | 240 | 190 | 200 | 32 | 77 | 315 | 295 | 225 |

[a] Averaged density and speed of I-405 and Sepulveda combined, weighted by magnitude of traffic flow from each roadway. Density rounded to nearest 5 when reporting more than two significant figures. Refer to Section 2.4 for details.

each respective day's seasonal average. Finally, weekday-to-weekday spillover (e.g., from Friday July 15 to the preceding or following Friday, July 8 or 22) was insubstantial, since the hourly average traffic flows were comparable. These findings are in agreement with a recently published comprehensive report of traffic behavior by the Institute of Transportation Studies at the UCLA Ralph & Goldy Lewis Center for Regional Policy Studies (Rosario et al., 2012). They also found that traffic did not shift in time and reported reduced traffic flow on alternate freeways and surface street arterial routes. In addition, they found public transportation ridership decreased on the closure Saturday.

The observed traffic and pollutant reductions as a result of the closure event are limited to a proof-of-concept for air quality improvements resulting from voluntary traffic reductions. We acknowledge the closure-event occurred on a weekend, which at our study site has a different traffic demand versus time relationship than weekdays. However a study of temporary closures during summer 2008 of the I-5 freeway in Sacramento, CA demonstrated work-related and non-work related travel behavior were similar and suggested travel demand management should be applied to non-work and commuter travel similarly (Yun et al., 2011). Thus, if the closure event was scheduled on a weekday, we are uncertain how traffic flow would change beyond the axiomatic traffic flow reduction on the closure segment of the I-405 freeway. Finally, we acknowledge a short scheduled closure event may elicit a different voluntary traffic behavioral response than a longer-term road closure. For example, during a three-week voluntary effort to reduce automobile travel during the 1984 Olympic Games in Los Angeles, residents abstained from roadway usage only until they realized large-scale gridlock did not materialize (Giuliano, 1988).

### 3.1.3. Fixed-site PNC and $PM_{2.5}$

Fig. 2 shows PNC and $PM_{2.5}$ concentrations upwind and downwind of the freeway obtained from the fixed-site locations. The boxes represent the interquartile range, the whiskers indicate one and a half times the interquartile range, and the regions bounded by the "X" symbols denote the middle 95 percent of the data. One-minute resolution data were used for $PM_{2.5}$ and 2-min resolution data for PNC. For pollutants measured on both sides of the freeway, downwind variability was larger than upwind variability, presumably due to the stronger influence of intermittent emissions from Sepulveda or the heterogeneous nature of high- and low-emitting vehicles from I-405.

Shown in Fig. 2a, daily median PNCs upwind ranged from 2000 to 6000 particles $cm^{-3}$; there were no substantial trends with respect to day of week. Thus, the upwind location was not directly influenced by freeway emissions. Downwind median PNCs ranged from 5000 to 11,000 particles $cm^{-3}$ during non-closure and $\sim$4000 particles $cm^{-3}$ during closure. PNCs were 31%, 83%, and 63% lower for closure conditions for Friday, Saturday, and Sunday (July 15 through 17) respectively, than the average non-closure increases in PNC. We discuss PNCs further in relationship to UFP emission factors in a later section.

Shown in Fig. 2b, daily median $PM_{2.5}$ upwind ranged from 6.3 to 18.0 $\mu g\ m^{-3}$ and downwind ranged from 8.8 to 21.7 $\mu g\ m^{-3}$, respectively. Across the entire campaign, median $PM_{2.5}$ was 2.0 $\mu g\ m^{-3}$ (14%) higher downwind than upwind. Within each day, the variance and hourly average $PM_{2.5}$ time series data, measured at both sites, generally track each other starting from a higher concentration at 10:00 decreasing to a lower concentration by 20:00 (not shown). The difference in upwind and downwind concentrations was greater on Fridays than on Saturdays or Sundays. Overall, even on Fridays, it does not appear $PM_{2.5}$ was a strong indicator of primary traffic emissions near roadways which is not surprising given a large fraction of $PM_{2.5}$, in general, comes from regional photochemical reactions (Zheng et al., 2002). At both upwind and downwind sites, there was a greater variability post-closure than closure as evidenced by taller boxes on Friday and Saturday but not Sunday. There were also some concentration distribution shifts shown by the changing median. For instance, on post-closure Saturday the median was closer to the 75th percentile whereas on the closure Sunday the median was closer to the 25th percentile.

The upwind $PM_{2.5}$ for the closure period was 55%, 39%, and 49% lower for the closure Friday through Sunday, respectively, compared with the post-closure period. We compare the closure to post-closure period because of the similar meteorology (Section 3.1.1). These closure-period $PM_{2.5}$ decreases may suggest emissions reduction on a regional scale because the upwind fixed site was not directly impacted by I-405 traffic emissions. We compare regional $PM_{2.5}$ and freeway traffic flow on the closure Saturday July 16 in Section 3.3 to test whether the closure event elicited traffic reductions elsewhere in the South Coast Air Basin sufficient to reduce $PM_{2.5}$ regionally.

Average downwind BC during non-closure conditions were 2.3, 1.4 and 1.3 $\mu g\ m^{-3}$ on Friday through Sunday, respectively. During the closure period, downwind BC was 25%, 62% and 65% lower, respectively. Since near-roadway BC has been linked strongly to HDDT activity (e.g. Miguel et al., 1998; Zhu et al., 2002a), and non-closure Friday BC was nearly twice weekend BC, weekend HDDT flow at our study location likely decreased. This would be consistent with HDDT flow patterns in the South Coast Air Basin which typically declines on weekends between 67 and 83% (Sullivan, 2004). However, PeMS truck flow data at our study site were unreliable and we were unable to ascertain this relationship with our data (see Supplementary material, Sections 4 and 5).

### 3.1.4. Fixed-site particle size distributions

Saturday UFP size distributions from the fixed-site monitors upwind and downwind are shown as contour plots in Fig. 3, where the *x*-axis indicates the time, the *y*-axis the particle size (log scale), and the color intensity indicates normalized particle number concentration (dN/dLogDp). The same concentration scale was used for all days, both upwind and downwind. Upwind size distributions (Fig. 3a–c) show how even with similar meteorology (Table 2), particle size distribution and concentration can vary. Upwind contours in Fig. 3b and c show PNC was somewhat higher during closure than post-closure. In general, peak concentrations were at $\sim$65 nm and were the highest during mornings, reached a low during the mid-afternoons, and increased again in the evenings. Downwind size distributions (Fig. 3d–f) generally resemble upwind size distributions plus fresh traffic emissions. Most notably, the intermittent nucleation mode ($\sim$30 nm) was nearly absent downwind during closure.

Daily average particle size distributions from Saturdays and Sundays are shown in Fig. 4. Bimodal distributions were observed during non-closure Saturdays and Sundays approximately at 20 and 65 nm, when daily traffic flow was >18,800 vehicles $hour^{-1}$. This is because during primary dilution (the initial 1–3 s after exhaust leave the tailpipe), hot vapors condense and smaller particles are formed with $\sim$70% of particles < 50 nm (Morawska et al., 2008). During the closure, a unimodal distribution was present downwind (Fig. 4b). Daily average I-405 flows were 2500 and 6900 vehicles $hour^{-1}$ for the closure Saturday and Sunday respectively. A bimodal distribution with a lower concentration "sub-mode" at $\sim$16 nm was observed on Sunday July 17 (Fig. 4e). On Sunday July 17, the freeway was closed until 12:00 when it was re-opened and traffic flow resumed to $\sim$50% of non-closure Sunday flow.

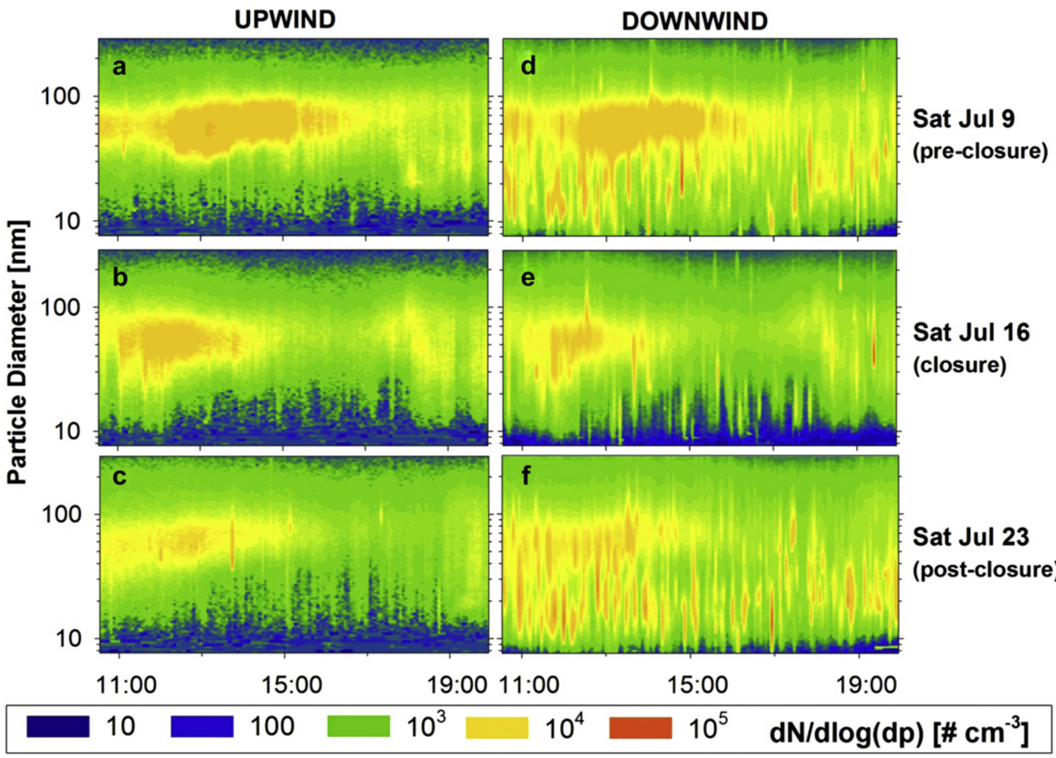


**Fig. 3.** Typical contour plot of UFP number-based size distributions for Saturdays pre-, during-, and post-closure (a–c) upwind and (d–f) downwind of I-405.

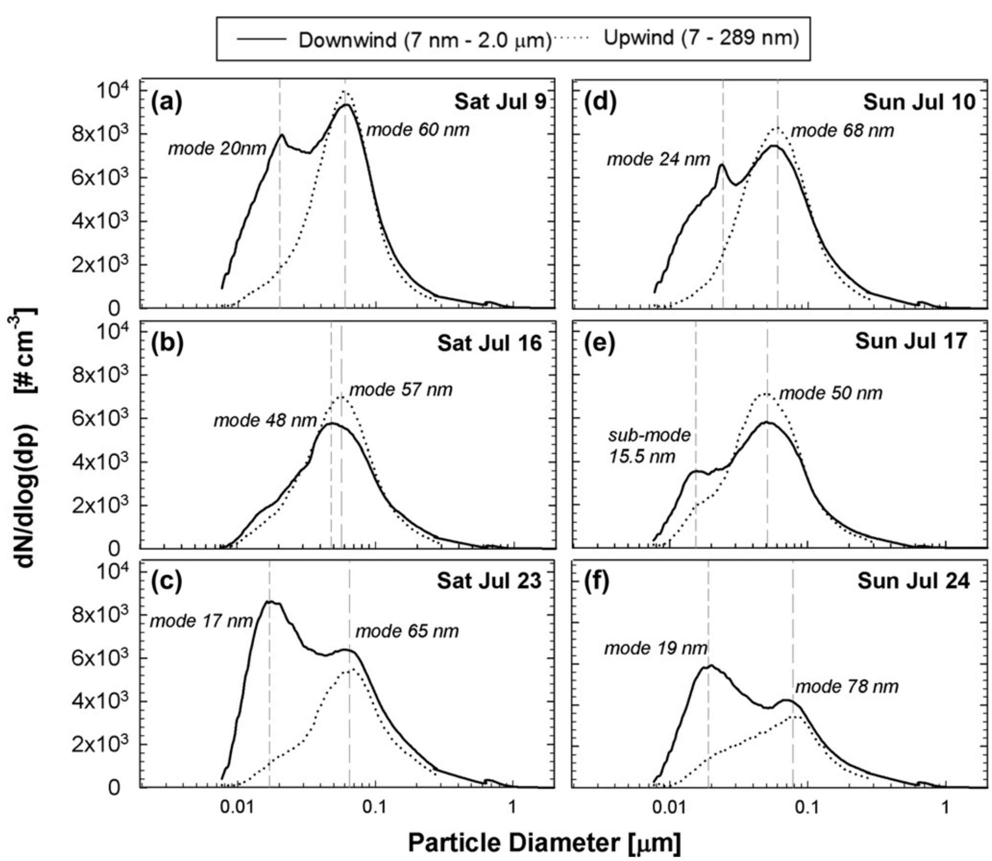


**Fig. 4.** Daily average size distributions upwind and downwind of I-405 for pre-, during-, and post-closure (a–c) Saturdays and (d–f) Sundays.

Average traffic flow during closure was 2500 vehicles hour$^{-1}$ and no daily average nucleation mode was observed (Fig. 4). Previous studies have shown ambient PM can serve as a deposition surface for UFPs (Charron and Harrison, 2003; Harrison and Jones, 2005). Accordingly, nucleation mode UFPs emitted from the transit corridor during closure may have deposited onto the surfaces of pre-existing PM. Our non-closure data also supported this hypothesis; taller and more broad nucleation mode peaks were observed post- than pre-closure, which corresponded to lower and higher upwind accumulation mode concentrations, respectively (Fig. 4a, d, c and f). We acknowledge our upwind size distribution data are limited to particle diameters <289 nm and do not adequately reflect total upwind PM surface area. The different accumulation mode concentrations upwind and downwind were not statistically significant as shown at the daily average level. In addition, across shorter (~1 h) averaging periods, the variability of observations was also high. We suggest future studies analyze broader ranges of controlled traffic flows at higher sampling resolutions.

#### 3.1.5. Mobile measurement platform for PNC, NO, and PAH

Average pollutant concentration profiles obtained with high spatial resolution (~10 m) during the MMP sampling periods are displayed in Fig. 5. Daily profiles of pollutants show that pollutant concentrations peaked ~60 m downwind from the freeway median. As discussed in detail in Choi et al. (in press), this peak location is likely caused by freeway geometry. Because the I-405 is elevated above the surface of Constitution, freeway plumes are transported farther downwind before reaching the ground. Higher peak concentrations of UFP, NO, and PAH were observed on pre-closure Saturday than for the post-closure Saturday, accompanied by higher far downwind (>250 m) concentrations. Given I-405 traffic flow was similar on both Saturdays (Table 2), weaker prevailing winds on Saturday July 9 are likely the explanation for the increase in relative concentrations of pollutants between the pre- and post-closure Saturdays. However, measurement ranges were large for all three pollutants on each day, possibly due to the transient nature of higher- and lower-emitting vehicles, traffic flow conditions, and dilution or dispersion.

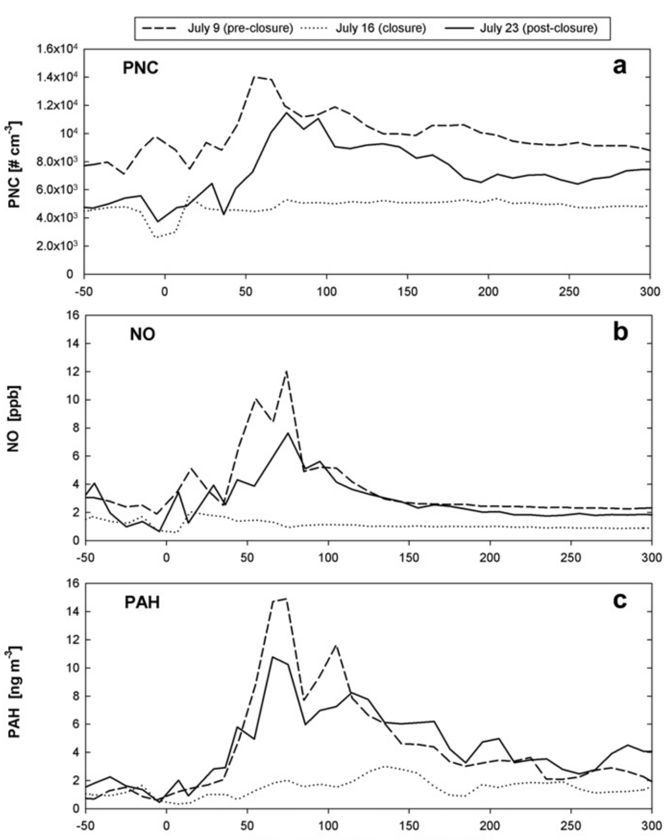


**Fig. 5.** Concentrations of (a) PNC, (b) NO, and (c) PAH at several distances from I-405 median.

Fig. 6 shows contour plots of size distribution, where the *x*-axis indicates the distance from freeway median, the *y*-axis indicates the particle diameter (log scale), and the color intensity indicates normalized particle number concentration (dN/dLogDp). Each panel represents twelve roundtrips, binned and averaged by location as determined by the onboard GPS instrument. Traffic flow did not vary much throughout the day on Saturdays. This is shown by the low standard deviations of traffic in Table 2, and also more generally for weekend traffic flow plotted as a function of time in Fig. S4·Supplementary material, Section 3). In both the upwind and downwind areas (>150 m), a unimodal particle mode was measured at ~52 nm. This is consistent with particle size distributions measured at the fixed sites, since the peak accumulation mode size was ~10 nm smaller with the FMPS aboard the MMP compared to the upwind fixed-site SMPS (refer to Supplementary material, Section 2). The nucleation mode particles disappeared much more quickly than accumulation mode particles for distances <150 m downwind due to dilution with air containing lower concentrations of nucleation mode particles but higher concentrations of accumulation mode particles, and coagulation losses to larger particles (Choi et al., in press; Zhu et al., 2002b). Distinct high particle concentrations at distances ~50–~150 m downwind from the freeway were observed in the nucleation modes (~11 nm) on both the pre- and post-closure Saturdays, but not during the closure (Fig. 6b), consistent with the notion that vehicular UFP emissions dominate nucleation mode particles as shown in Fig. 4. Another interesting feature of the size distribution (Fig. 6) is that the accumulation mode was measured at ~52 nm on both pre- and post-closure Saturdays compared to measurement at ~40 nm during the closure Saturday. The reduction in accumulation mode particle size during the closure period was also observed at the fixed measurement site with the SMPS (Fig. 4). This is likely due to the absence of freshly emitted organic vapors and/or nucleation mode particles from the freeway that condense/coagulate and result in growth of accumulation mode particles. A detailed investigation of particle dynamics to prove this hypothesis is, however, beyond the scope of this study.

### 3.2. Freeway UFP emissions in 2001 and 2011

#### 3.2.1. UFP emission factors

We found non-closure PNC EFs[6] were 5.6, 3.1 and 3.8 × $10^{14}$ particles (7–289 nm) per kg fuel, or 5.0, 2.7, and 3.4 × $10^{13}$ particles vehicle$^{-1}$ km$^{-1}$, for Friday through Sunday respectively. EFs for weekday traffic flow measured at this location in 2001 reported in Zhang et al. (2005) ranged 9.6 × $10^{13}$–4.7 × $10^{14}$ vehicle$^{-1}$ km$^{-1}$. The PNC ranges measured in 2001 were slightly narrower (6–220 nm) than in 2011 (7–289 nm). To test if this impacted our analysis, we performed size-segregated PNC EF analyses within the following size ranges: 7.6–30 nm, 30–50 nm, 50–100 nm, and 100–289 nm. On average, these size bins

[6] CARB: California Air Resources Board.

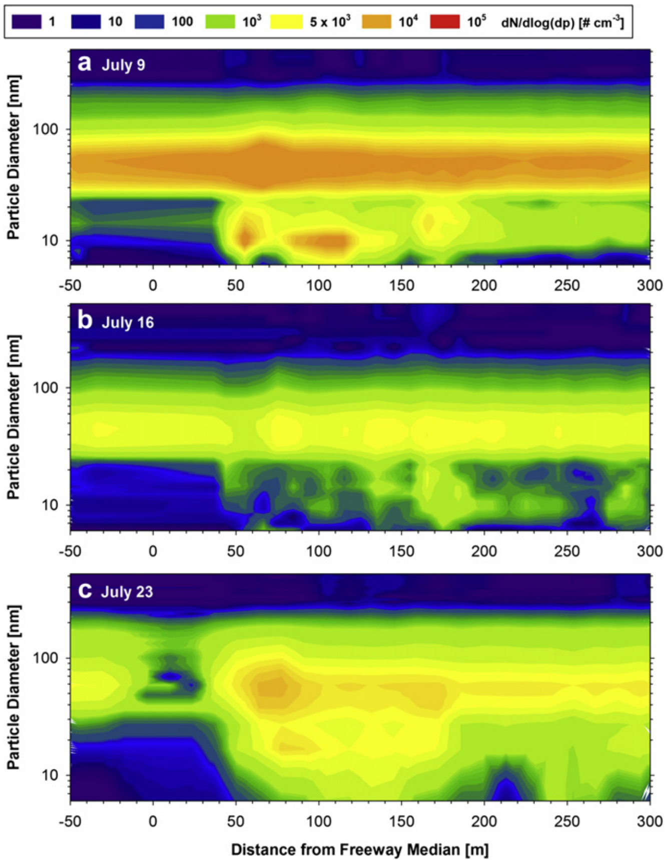


**Fig. 6.** Contour plots of particle size distributions as a function of distance from I-405 on Saturday (a) July 9 (pre-closure), (b) July 16 (closure) and (c) July 23 (post-closure).

contributed of 59, 20, 18, and 3% of the emissions, respectively ($4.6 \times 10^{14}$ particles 7.6–289 nm kg fuel$^{-1}$) for 2011. Since ~3% near-roadway emissions in 2011 were from particle diameters >100 nm, we assume differences due to size range measurement are negligible.

### 3.2.2. Fleet emission comparisons between 2001 and 2011

The delta PNC (i.e. the difference between downwind and upwind PNC) measured between 50 m upwind and downwind from the freeway median decreased by 51% between 2001 and 2011 (from 112,500 to 55,000 particles cm$^{-3}$). Meanwhile, weekday traffic flow has increased by 23% at the study site (I-405 and Sepulveda flow) from 2001 to 2011. After accounting for this increased traffic flow (from 13,900 in 2001 to 17,100 vehicles hour$^{-1}$ on non-closure Fridays in 2011), the delta PNC decreased in total by 60%.

Over the past decade, near-roadway studies elsewhere found a 50% PNC reduction over an eight-year period in Rochester, NY (Wang et al., 2011) and 21% a reduction over a five-year period for PNC < 50 nm in Toronto, Canada (Sabaliauskas et al., 2012). In the United States, the proportion of four cylinder engines increased from 30% to 43% (Snyder, 2011). At the study location, the total quantity of HDDTs did not appreciably change over this decade and remains <5% of the fleet (2011 weekday HDDTs were 2.7% of total flow, see Supplementary material). A 2006 California Air Resource Board (CARB)[6] fuel regulation required the reduction of sulfur content from 500 to 15 ppm (CARB, 2004a). Morawska et al. (2008) cites five studies indicating lower PNC emissions when switching from a higher to lower sulfur content around these concentration ranges. CARB also further tightened new HDDT engine emissions to

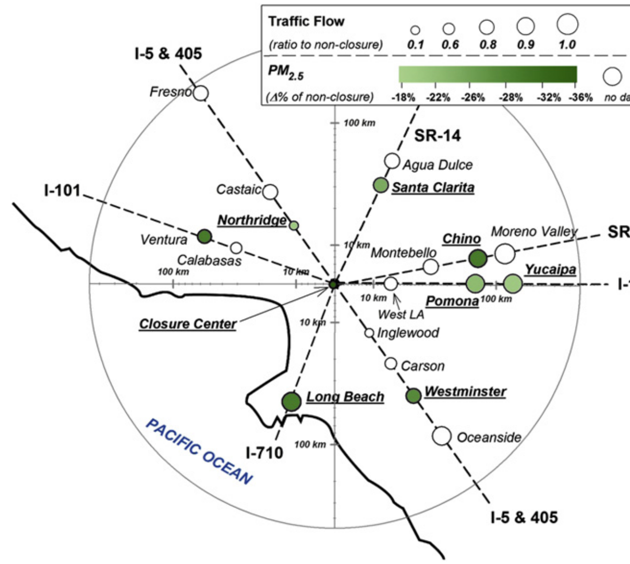


**Fig. 7.** Regional freeway traffic flows and ambient $PM_{2.5}$ changes during the I-405 closure on Saturday July 16 relative to four control days. The area of each circle is proportional to the traffic flow change. The color of each circle represents any change in $PM_{2.5}$. A legend is shown within the figure.

0.1 and 0.01 g total PM per brake horsepower-hr, in 2004 and 2007, respectively (CARB, 2004b, 2008). Considering the greater time spans between the measurements, findings from our study are more or less similar to findings from other studies. Differences could be due to differences in vehicle fleet composition, regulatory jurisdiction, study design and/or time periods compared.

### 3.3. Regional traffic and $PM_{2.5}$

Fig. 7 illustrates selected major freeways that connect to the I-405 closure location. Distance from the closure site is shown on a logarithmic scale on each axis. The direction to which each freeway is shown is approximate. We report the traffic flow data by circle size and the $PM_{2.5}$ data by fill color; ratios are reported as a proportion of during-closure conditions on Saturday July 16 to non-closure conditions on the four control Saturdays.

The figure shows freeway traffic flow decreased by 5–90% during closure indicating the I-405 closure resulted in basin-wide freeway traffic reductions, as noted by the size of the bubble in the plot. Traffic reductions along the I-405/I-5 corridor were most substantial and extended as far north as Fresno (380 km) and as far south as Oceanside (160 km). While extensive data are not available, surface street data were also lower in the area around the closure (Rosario et al., 2012). Within the South Coast Air Basin, $PM_{2.5}$ decreased between 18 and 36% at each ambient monitoring location. The largest $PM_{2.5}$ reduction was observed at the closure center, which also had the greatest traffic reduction. However, there was otherwise little geographic correlation between traffic and $PM_{2.5}$ reductions. The data suggest this I-405 closure event led to a regional traffic reduction that contributed to an overall average 25% $PM_{2.5}$ reduction observed in multiple locations.

## 4. Conclusions

This study measured air quality and traffic patterns near I-405 in West Los Angeles before, during, and after a 36-h scheduled closure event. This study was a natural experiment to investigate the traffic behavioral response and resulting air quality impacts on local and regional scales. Local downwind reductions for the closure period were 83% PNC, 36% $PM_{2.5}$, and 62% BC. Near-roadway UFP size distribution depended largely on traffic flow. During closure conditions (2500 vehicles hour$^{-1}$), no nucleation mode was observed and the accumulation mode measured by the fixed-site SMPS shifted from ~60 nm to 50 nm. Freeway corridor reductions that occurred during the closure extended as far north as Fresno (380 km) and south to Oceanside (160 km) and regional $PM_{2.5}$ reduced between 18 and 36% at various locations throughout the South Coast Air Basin. Our study illustrates the significant air quality improvement resulting from a large-scale traffic reduction due to a short, scheduled major freeway closure event. Non-closure SMPS measurements indicated weekday PNC declined by 60% between 2001 and 2011. These substantial reductions suggest the efficacy of emission control programs over this decade.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2012.10.020.

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